Orthogonal frequency-division multiplexing

From Wikipedia, the free encyclopedia

Orthogonal Frequency-Division Multiplexing (OFDM) — essentially identical to **Coded OFDM (COFDM)** — is a digital multi-carrier modulation scheme, which uses a large number of closely-spaced orthogonal *sub-carriers*. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation) at a low symbol rate, maintaining data rates similar to conventional *single-carrier* modulation schemes in the same bandwidth. In practice, OFDM signals are generated and detected using the Fast Fourier transform algorithm.

OFDM has developed into a popular scheme for wideband digital communication, wireless as well as over copper wires.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions — for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath — without complex equalization filters. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. Low symbol rate makes the use of a guard interval between symbols affordable, making it possible to handle time-spreading and eliminate inter-symbol interference (ISI).

Topics in Modulation techniques

Analog modulation

AM | SSB | FM | PM | QAM

Digital modulation

OOK | FSK | ASK | PSK | QAM | APSK | MSK | CPM | PPM | TCM | **OFDM**

Spread spectrum

FHSS | DSSS

edit (http://en.wikipedia.org/w/index.php?title=Template:Modulation_techniques&action=edit)

Contents

Example of applications

The following list is a summary of existing OFDM based standards and products. For further details, see the #Usage section in the end of the article.

Cable

- ADSL and VDSL broadband access via POTS copper wiring.
- Power line communication (PLC).
- Multimedia over Coax Alliance (MoCA) home networking.

Wireless

- The wireless LAN radio interfaces IEEE 802.11a, g and HIPERLAN/2.
- The digital radio systems systems DAB/EUREKA 147, DAB+, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB.
- The terrestrial digital TV system DVB-T.
- The terrestrial mobile TV systems DVB-H, T-DMB, ISDB-T and MediaFLO forward link.
- The beyond 3G cellular communication systems Flash-OFDM and 3GPP Long Term Evolution LTE.
- The Wireless MAN / Fixed broadband wireless access (BWA) standards IEEE 802.16 (or WiMAX) and HIPERMAN.
- The Mobile Broadband Wireless Access (MBWA) standards IEEE 802.20, IEEE 802.16e (Mobile WiMAX) and WiBro.
- The wireless Personal Area Network (PAN) Ultra wideband (UWB) IEEE 802.15.3a implementation suggested by WiMedia Alliance.

Key features

Summary of advantages

- Can easily adapt to severe channel conditions without complex equalization
- Robust against narrow-band co-channel interference
- Robust against Intersymbol interference (ISI) and fading caused by multipath propagation
- High spectral efficiency
- Efficient implementation using FFT
- Low sensitivity to time synchronization errors
- Tuned sub-channel receiver filters are not required (unlike conventional FDM)
- Facilitates Single Frequency Networks, i.e. transmitter macrodiversity.

Summary of disadvantages

- Sensitive to Doppler shift.
- Sensitive to frequency synchronization problems.
- High peak-to-average-power ratio (PAPR), requiring more expensive transmitter circuitry, and giving poor power efficiency.

Characteristics and principles of operation

Orthogonality

In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-channels is eliminated and inter-carrier guard bands are not required. This greatly simplifies the design of both the transmitter and the receiver; unlike conventional FDM, a separate filter for each sub-channel is not required.

The orthogonality also allows high spectral efficiency, near the Nyquist rate. Almost the whole available frequency band can be utilized. OFDM generally has a nearly 'white' spectrum, giving it benign electromagnetic interference properties with respect to other co-channel users.

The orthogonality allows for efficient modulator and demodulator implementation using the FFT algorithm. Although the principles and some of the benefits have been known since the 1960s, OFDM is popular for wideband communications today by way of low-cost digital signal processing components that can efficiently calculate the FFT.

OFDM requires very accurate frequency synchronization between the receiver and the transmitter; with frequency deviation, the sub-carriers shall no longer be orthogonal, causing *inter-carrier interference* (ICI), i.e. cross-talk between the sub-carriers. Frequency offsets are typically caused by mismatched transmitter and receiver oscillators, or by Doppler shift due to movement. Whilst Doppler shift alone may be compensated for by the receiver, the situation is worsened when combined with multipath, as reflections will appear at various frequency offsets, which is much harder to correct. This effect typically worsens as speed increases, and is an important factor limiting the use of OFDM in high-speed vehicles. Several techniques for ICI suppression are suggested, but they may increase the receiver complexity.

Guard interval for elimination of inter-symbol interference

One key principle of OFDM is that since low symbol rate modulation schemes (i.e. where the symbols are relatively long compared to the channel time characteristics) suffer less from intersymbol interference caused by multipath, it is advantageous to transmit a number of low-rate streams in parallel instead of a single high-rate stream. Since the duration of each symbol is long, it is feasible to insert a guard interval between the OFDM symbols, thus eliminating the intersymbol interference.

The guard interval also eliminates the need for a pulse-shaping filter, and it reduces the sensitivity to time synchronization problems.

> **A simple example:** If one sends a million symbols per second using conventional single-carrier modulation over a wireless channel, then the duration of each symbol would be one microsecond or less. This imposes severe constraints on synchronization and necessitates the removal of multipath interference. If the same million symbols per second are spread among one thousand sub-channels, the duration of each symbol can be longer by a factor of thousand, i.e. one millisecond, for orthogonality with approximately the same bandwidth. Assume that a guard interval of 1/8 of the symbol length is inserted between each symbol. Intersymbol interference can be avoided if the multipath time-spreading (the time between the reception of the first and the last echo) is shorter than the guard interval, i.e. 125 microseconds. This corresponds to a maximum difference of 37.5 kilometers between the lengths of the paths.

The cyclic prefix, which is transmitted during the guard interval, consists of the end of the OFDM symbol copied into the guard interval, and the guard interval is transmitted followed by the OFDM symbol. The reason that the guard interval consists of a copy of the end of the OFDM symbol is so that the receiver will integrate over an integer number of sinusoid cycles for each of the multipaths when it performs OFDM demodulation with the FFT.

Although the guard interval only contains redundant data, which means that it reduces the capacity, some OFDM-based systems, such as some of the broadcasting systems, deliberately use a long guard interval in order to allow the transmitters to be spaced farther apart in an SFN, and longer guard intervals allow larger SFN cell-sizes. A rule of thumb for the maximum distance between transmitters in an SFN is equal to the distance a signal travels during the guard interval — for instance, a guard interval of 200 microseconds would allow transmitters to be spaced 60 km apart.

Simplified equalization

The effects of frequency-selective channel conditions, for example fading caused by multipath propagation, can be considered as constant (flat) over an OFDM sub-channel if the sub-channel is sufficiently narrow-banded, i.e. if the number of sub-channels is sufficiently large. This makes equalization far simpler at the receiver in OFDM in comparison to conventional single-carrier modulation. The equalizer only has to multiply each sub-carrier by a constant value, or a rarely changed value.

> **Our example:** The OFDM equalization in the above numerical example would require $N = 1000$ complex multiplications per OFDM symbol, i.e. one million multiplications per second, at the receiver. The FFT algorithm requires $N\log_2 N = 10.000$ complex-valued multiplications per OFDM symbol, i.e. *10 million multiplications per second*, at both the receiver and transmitter side. This should be compared with the corresponding one million symbols/second single-carrier modulation case mentioned in the example, where the

equalization of 125 microseconds time-spreading using a FIR filter would require 125 multiplications per symbol, i.e. *125 million multiplications per second.*

Some of the sub-carriers in some of the OFDM symbols may carry pilot signals for measurement of the channel conditions, i.e. the equalizer gain for each sub-carrier. Pilot signals may also be used for synchronization.

If differential modulation such as DPSK or DQPSK is applied to each sub-carrier, equalization can be completely omitted, since these schemes are insensitive to slowly changing amplitude and phase distortion.

Channel coding and interleaving

OFDM is invariably used in conjunction with channel coding (forward error correction), and almost always uses frequency and/or time interleaving.

Frequency (subcarrier) interleaving increases resistance to frequency-selective channel conditions such as fading. For example, when a part of the channel bandwidth is faded, frequency interleaving ensures that the bit errors that would result from those subcarriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated. Similarly, time interleaving ensures that bits that are originally close together in the bit-stream are transmitted far apart in time, thus mitigating against severe fading as would happen when travelling at high speed.

However, time interleaving is of little benefit in slowly fading channels, such as for stationary reception, and frequency interleaving offers little to no benefit for narrowband channels that suffer from flat-fading (where the whole channel bandwidth is faded at the same time).

The reason why interleaving is used on OFDM is to attempt to spread the errors out in the bit-stream that is presented to the error correction decoder, because when such decoders are presented with a high concentration of errors the decoder is unable to correct all the bit errors, and a burst of uncorrected errors occurs.

A common type of error correction coding used with OFDM-based systems is convolutional coding, which is often concatenated with Reed-Solomon coding. Convolutional coding is used as the inner code and Reed-Solomon coding is used for the outer code — usually with additional interleaving (on top of the time and frequency interleaving mentioned above) in between the two layers of coding. The reason why this combination of error correction coding is used is that the Viterbi decoder used for convolutional decoding produces short errors bursts when there is a high concentration of errors, and Reed-Solomon codes are inherently well-suited to correcting bursts of errors.

Newer systems, however, usually now adopt the near-optimal types of error correction coding that use the turbo decoding principle, where the decoder iterates towards the desired solution. Examples of such error correction coding types include turbo codes and LDPC codes. These codes only perform close to the Shannon limit for the Additive White Gaussian Noise (AWGN) channel, however, and some systems that have adopted these codes have concatenated them with either Reed-Solomon (for example on the MediaFLO system) or BCH codes (on the DVB-S2 system) to improve performance further over the wireless channel.

Adaptive transmission

The resilience to severe channel conditions can be further enhanced if information about the channel is sent over a return-channel. Based on this feedback information, adaptive modulation, channel coding and power allocation may be applied across all sub-carriers, or individually to each sub-carrier. In the latter case, if a particular range of frequencies suffers from interference or attenuation, the carriers within that range can be disabled or made to run slower by applying more robust modulation or error coding to those sub-carriers.

The term **discrete multitone modulation (DMT)** denotes OFDM based communication systems that adapt the transmission to the channel conditions individually for each sub-carrier, by means of so called **bit-loading**. Examples are ADSL and VDSL.

The upstream and downstream speeds can be varied by allocating either more or fewer carriers for each purpose. Some forms of Rate-adaptive DSL use this feature in real time, so that bandwidth is allocated to whichever stream needs it most.

OFDM extended with multiple access

OFDM in its primary form is considered as a digital modulation technique, and not a multi-user channel access technique, since it is utilized for transferring one bit stream over one communication channel using one sequence of OFDM symbols. However, OFDM can be combined with multiple access using time, frequency or coding separation of the users.

In Orthogonal Frequency Division Multiple Access (OFDMA), frequency-division multiple access is achieved by assigning different OFDM sub-channels to different users. OFDMA supports differentiated quality-of-service by assigning different number of sub-carriers to different users in a similar fashion as in CDMA, and thus complex packet scheduling or media access control schemes can be avoided. OFDMA is used in the uplink of the IEEE 802.16 Wireless MAN standard, commonly referred to as WiMAX.

In Multi-carrier code division multiple access (MC-CDMA), also known as OFDM-CDMA, OFDM is combined with CDMA spread spectrum communication for coding separation of the users. Co-channel interference can be mitigated against, meaning that manual fixed channel allocation (FCA) frequency planning is simplified, or complex dynamic channel allocation (DCA) schemes are avoided.

Space diversity

In OFDM based wide area broadcasting, receivers can benefit from receiving signals from several spatially-dispersed transmitters simultaneously, since transmitters will only destructively interfere with each other on a limited number of sub-carriers, whereas in general they will actually reinforce coverage over a wide area. This is very beneficial in many countries, as it permits the operation of national single-frequency networks (SFNs), where many transmitters send the same signal simultaneously over the same channel frequency. SFNs utilise the available spectrum more effectively than conventional multi-frequency broadcast networks (MFN), where program content is replicated on different carrier frequencies. SFNs also result in a diversity gain in receivers situated midway between the transmitters. The coverage area is increased and the outage probability decreased in comparison to an MFN, due to increased received signal strength averaged over all sub-carriers.

Single-frequency networks is a form of transmitter macrodiversity.

OFDM may be combined with other forms of space diversity, for example antenna arrays and MIMO channels. This is done in the IEEE802.11n Wireless LAN standard.

Linear transmitter power amplifier

An OFDM signal exhibits a high peak-to-average power ratio (PAPR) because the independent phases of the sub-carriers mean that they will often combine constructively. Handling this high PAPR requires:

- a high-resolution digital-to-analog converter (DAC) in the transmitter
- a high-resolution analog-to-digital converter (ADC) in the receiver
- a linear signal chain.

Any non-linearity in the signal chain will cause intermodulation distortion that

- raises the noise floor
- may cause intersymbol interference
- generates out-of-band spurious radiation.

The linearity requirement is demanding, especially for transmitter RF output circuitry where amplifiers are often designed to be non-linear in order to minimise power consumption. In practical OFDM systems a small amount of peak clipping is allowed to limit the PAPR in a judicious tradeoff against the above consequences. However the transmitter output filter which is required to reduce out-of-band spurrii to legal levels has the effect of restoring peak levels that were clipped, so clipping is not an effective way to reduce PAPR.

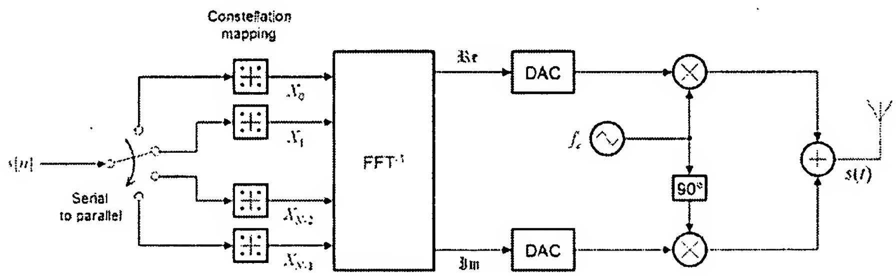
Although the spectral efficiency of OFDM is attractive for both terrestrial and space communications, the high PAPR requirements have so far limited OFDM applications to terrestrial systems.

Ideal system model

This section describes a simple idealized OFDM system model suitable for a time-invariant AWGN channel.

Transmitter

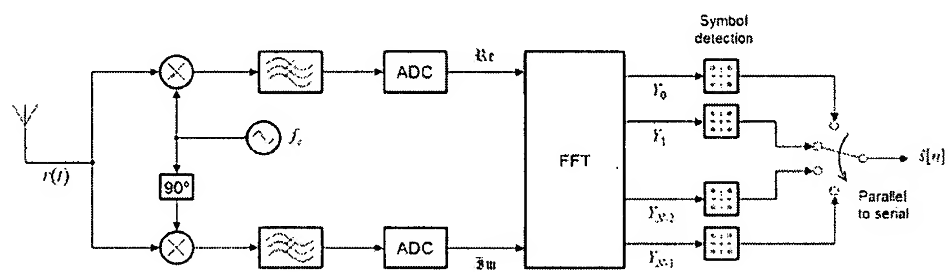
An OFDM carrier signal is the sum of a number of orthogonal sub-carriers, with baseband data on each sub-carrier being independently modulated commonly using some type of quadrature amplitude modulation (QAM) or phase-shift keying (PSK). This composite baseband signal is typically used to modulate a main RF carrier.



$s[n]$ is a serial stream of binary digits. By inverse multiplexing, these are first demultiplexed into N parallel streams, and each one mapped to a (possibly complex) symbol stream using some modulation constellation (QAM, PSK, etc.). Note that the constellations may be different, so some streams may carry a higher bit-rate than others.

An inverse FFT is computed on each set of symbols, giving a set of complex time-domain samples. These samples are then quadrature-mixed to passband in the standard way. The real and imaginary components are first converted to the analogue domain using digital-to-analogue converters (DACs); the analogue signals are then used to modulate cosine and sine waves at the carrier frequency, f_c, respectively. These signals are then summed to give the transmission signal, $s(t)$.

Receiver



The receiver picks up the signal $r(t)$, which is then quadrature-mixed down to baseband using cosine and sine waves at the carrier frequency. This also creates signals centered on $2f_c$, so low-pass filters are used to reject these. The baseband signals are then sampled and digitised using analogue-to-digital converters (ADCs), and a forward FFT is used to convert back to the frequency domain.

This returns N parallel streams, each of which is converted to a binary stream using an appropriate symbol detector. These streams are then re-combined into a serial stream, $\hat{s}[n]$, which is an estimate of the original binary stream at the transmitter.

Mathematical description

If N sub-carriers are used, and each sub-carrier is modulated using M alternative symbols, the OFDM symbol alphabet consists of M^N combined symbols.

The low-pass equivalent OFDM signal is expressed as:

$$\nu(t) = \sum_{k=0}^{N-1} X_k e^{i2\pi kt/T}, \quad 0 \le t < T,$$

where $\{X_k\}$ are the data symbols, N is the number of sub-carriers, and T is the OFDM symbol time. The sub-carrier spacing of $1 / T$ makes them orthogonal over each symbol period; this property is expressed as:

$$\frac{1}{T}\int_0^T \left(e^{i2\pi k_1 t/T}\right)^* \left(e^{i2\pi k_2 t/T}\right) dt$$
$$=\frac{1}{T}\int_0^T e^{i2\pi(k_2-k_1)t/T} dt = \delta_{k_1 k_2}$$

where $(\cdot)^*$ denotes the complex conjugate operator and δ is the Kronecker delta..

To avoid intersymbol interference in multipath fading channels, a guard interval of length T_g is inserted prior to the OFDM block. During this interval, a *cyclic prefix* is transmitted such that the signal in the interval $-T_g \leq t < 0$ equals the signal in the interval $(T - T_g) \leq t < T$. The OFDM signal with cyclic prefix is thus:

$$\nu(t) = \sum_{k=0}^{N-1} X_k e^{i2\pi kt/T}, \quad -T_g \leq t < T$$

The low-pass signal above can be either real or complex-valued. Real-valued low-pass equivalent signals are typically transmitted at baseband—wireline applications such as DSL use this approach. For wireless applications, the low-pass signal is typically complex-valued; in which case, the transmitted signal is up-converted to a carrier frequency f_c. In general, the transmitted signal can be represented as:

$$s(t) = \frac{1}{2}\Re\left\{\nu(t)e^{i2\pi f_c t}\right\}$$
$$= \sum_{k=0}^{N-1} |X_k| \cos\left(2\pi[f_c + k/T]t + \arg[X_k]\right)$$

Usage

OFDM system comparison table

Key features of some common OFDM based systems are presented in the following table.

Standard name	DAB Eureka 147	DVB-T	DVB-H	IEEE 802.11a	
Ratified year	1995	1997			
Frequency range of today's equipment	174 - 240, 1452 - 1492	470 - 862			MHz
Channel spacing B	1.712	8			MHz
Number of subcarriers N	192, 384, 768 or 1536	2K mode: 1705 8K mode: 6817			
Subcarrier modulation scheme	DQPSK	QPSK, 16QAM or 64QAM			
Total symbol length T_S		2K mode: 224 + Guard Interval 8K mode: 896 + Guard Interval			µs
Guard interval T_G		1/4, 1/8, 1/16, 1/32			Fraction of T_S
Subcarrier spacing $\Delta f = /(T_S - T_G) \approx B/N$		2K mode: 4464 8K mode: 1116			Hz
Net bit rate R	0.576 - 1.152	4.98 - 31.67 (typically 24)			MHz
Link spectral efficiency R/B	0.34 - 0.67	0.62 - 4.0			bit/s/Hz
Inner FEC	Conv coding with code rates 1/4, 3/8 or 1/2	Conv coding with code rates 1/2, 2/3, 3/4, 5/6 or 7/8			
Outer FEC (if any)	None	RS(204,188,t=8)			
Maximum travelling speed	200 - 600	53 - 185			km/h
Time interleaving depth	385	0.6 - 3.5			ms
Adaptive transmission (if any)	None	None			
Multiple access method (if any)	None	None			
Typical source coding	192 kbit/s MPEG2 Audio layer 2	4 Mbit/s MPEG2			

ADSL

OFDM is used in ADSL connections that follow the G.DMT(ITU G.992.1) standard, in which existing copper wires are used to achieve high-speed data connections.

Long copper wires suffer from attenuation at high frequencies. The fact that OFDM can cope with this frequency selective attenuation and with narrow-band interference are the main reasons it is frequently used in applications such as ADSL modems. However, DSL cannot be used on every copper pair; interference may become significant if more than 25% of phone lines coming into a central office are used for DSL.

For experimental amateur radio applications, users have even hooked up commercial off-the-shelf ADSL equipment to radio transceivers which simply shift the bands used to the radio frequencies the user has licensed.

Powerline Technology

OFDM is used by powerline devices to extend Ethernet connections to other rooms in a home through its power wiring. Adaptive modulation is particularly important with such a noisy channel as electrical wiring.

Wireless local area networks (LAN) and metropolitan area networks (MAN)

OFDM is also now being used in some wireless LAN and MAN applications, including IEEE 802.11a/g (and the defunct European alternative HIPERLAN/2) and WiMAX. IEEE 802.11a, operating in the 5 GHz band, specifies airside data rates ranging from 6 to 54 Mbit/s. Four different modulation schemes are used: BPSK, 4-QAM, 16-QAM, and 64-QAM, along with a number of convolutional encoding schemes. This allows the system to adapt to the optimum data rate vs. error rate for the current conditions.

Wireless personal area networks (PAN)

OFDM is also now being used in the WiMedia / Ecma-368 standard for high-speed wireless personal area networks in the 3.1-10.6 GHz ultrawideband spectrum. See www.wimedia.com.

Terrestrial digital radio and television broadcasting

Much of Europe and Asia has adopted OFDM for terrestrial broadcasting of digital television (DVB-T, DVB-H and T-DMB) and radio (EUREKA 147 DAB, Digital Radio Mondiale, HD Radio and T-DMB).

DVB-T

By Directive of the European Commission, all television services transmitted to viewers in the European Community must use a transmission system that has been standardized by a recognized European standardization body,[1] and such a standard has been developed and codified by the DVB Project, *Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television*.[2] Customarily referred to as DVB-T, the standard calls for the exclusive use of COFDM for modulation. DVB-T is now widely used in Europe and elsewhere for terrestrial digital TV.

COFDM vs. VSB

The question of the relative technical merits of COFDM versus 8VSB has been a subject of some controversy, especially between Europe and USA. The United States has rejected several proposals to adopt COFDM for its digital television services, and has instead opted for 8VSB (vestigial sideband modulation) operation.

One of the major benefits provided by COFDM is that it renders radio broadcasts relatively immune to multipath distortion and signal fading due to atmospheric conditions or passing aircraft. Proponents of COFDM argue that it resists multipath far better than 8VSB. Early 8VSB DTV (digital television) receivers often had difficulty receiving a signal in urban environments.

However, newer 8VSB receivers are far better at dealing with multipath, hence the difference in performance may diminish with advances in demodulator design. Moreover, 8VSB modulation requires less power to transmit a signal the same distance, i.e., the received carrier-to-noise threshold is lower for the same bit error rate. In less-populated areas, 8VSB may have an advantage because of this. In urban areas, however, COFDM is believed to offer better reception than 8VSB.

In practice, it may be impossible to settle this debate without empirical history. One difficulty in fully assessing the two systems' relative performance in multipath environments is that the spatial distribution of multipath cannot be modeled well. Due to the chaotic nature of multipath, the process is non-stationary, both temporally and spatially, in the stochastic sense. Thus, the probability distribution of impaired receiving locations is not tractable.

Digital radio

COFDM is also used for other radio standards, for digital audio broadcasting (DAB), the standard for digital audio broadcasting at VHF frequencies, and also for Digital Radio Mondiale (DRM), the standard for digital broadcasting at shortwave and mediumwave frequencies (below 30 MHz).

The USA again uses an alternate standard, a proprietary system developed by iBiquity dubbed "HD Radio". However, it uses COFDM as the underlying broadcast technology to add digital audio to AM (medium wave) and FM broadcasts.

Both Digital Radio Mondiale and HD Radio are classified as in-band on-channel systems, unlike Eureka 147 (DAB: Digital audio broadcasting) which uses separate VHF or UHF frequency bands instead.

BST-OFDM used in ISDB

The BST-OFDM (Band Segmented Transmission Orthogonal Frequency Division Multiplexing) system proposed for Japan — in the ISDB-T, ISDB-TSB and ISDB-C broadcasting systems — improves upon COFDM by exploiting the fact that some OFDM carriers may be modulated differently from others within the same multiplex. Some forms of COFDM already offer this kind of hierarchical modulation, though BST-OFDM is intended to make it more flexible. The 6 MHz television channel may therefore be "segmented", with different segments being modulated differently and used for different services.

It is possible, for example, to send an audio service on a segment that includes a segment comprised of a number of carriers, a data service on another segment and a television service on yet another segment - all within the same 6 MHz television channel. Furthermore, these may be modulated with different parameters so that, for example, the audio and data services could be optimized for mobile reception, while the television service is optimized for stationary reception in a high-multipath environment.

Ultra wideband

UWB (ultra wideband) wireless personal area network technology may also utilise OFDM, such as in Multiband OFDM (MB-OFDM). This UWB specification is advocated by the WiMedia Alliance (formerly by both the Multiband OFDM Alliance (MBOA) and the WiMedia Alliance, but the two have now merged), and is one of the competing UWB

radio interfaces.

Flash-OFDM

Flash-OFDM (Fast Low-latency Access with Seamless Handoff Orthogonal Frequency Division Multiplexing) is a system that is based on OFDM and specifies also higher protocol layers. It has been developed and is marketed by Flarion. Flash-OFDM has generated interest as a packet-switched cellular bearer, on which area it would compete with GSM and 3G networks. As an example, old 450 MHz frequency bands that were used by NMT-450 and C-Net C450 (both 1G analog networks, now mostly decommissioned) in Europe are already being licensed to Flash-OFDM operators. In Finland the license holder Digita (http://www.digita.fi/?lan=en) has begun deployment of its nationwide "@450" wireless network, operational in parts of the country since April 2007 and planned coverage of all of Finland in 2009.

American wireless carrier Sprint Nextel had stated plans (http://www.teleclick.ca/2006/03/sprint-nextel-plans-better-than-3g-mobile-multimedia-network/) for field testing Flash-OFDM (along with other wireless broadband network technologies) for their 4G offering, which will be deployed using the licenses they own nationwide in the 2.5 GHz frequency range. Sprint subsequently has decided to deploy the mobile version of WiMAX, which is based on SOFDMA, scalable orthogonal frequency division multiple access technology.

T-Mobile already offers Flash-OFDM connection to its subscribers in Slovakia. The maximum download speed is 5.3 Mbit/s, whereas upload speed is limited to 1.8 Mbit/s.

Citizens Telephone Cooperative launched a Flash-OFDM service to subscribers in parts of Virginia in March, 2006. The maximum speed available is 1.5 Mbit/s.[3]

Digiweb Ltd. launched a mobile broadband network using FLASH-OFDM technology at 872 MHz in July 2007 in Ireland and also will be launching in Norway. Voice handsets are not yet available at the time of writing (July 2007)

Butler Networks is currently trialing FLASH-OFDM technology in Denmark at the 872 MHz as well.

In The Netherlands, KPN-telecom will start a pilot around July 2007.

History

- 1957: Kineplex, multi-carrier HF modem
- 1966: Chang, Bell Labs: OFDM paper and US patent 3488445 (http://v3.espacenet.com/textdoc?DB=EPODOC&IDX=US3488445)
- 1971: Weinstein & Ebert proposed use of FFT and guard interval
- 1985: Cimini described use of OFDM for mobile communications
- 1985: Telebit Trailblazer Modem introduced incorporating a 512 carrier Packet Ensemble Protocol
- 1987: Alard & Lasalle: COFDM for digital broadcasting
- September 1988: TH-CSF LER, first experimental Digital TV link in OFDM, Paris area
- 1989: OFDM international patent application PCT/FR 89/00546, filed in the name of THOMSON-CSF, Fouche, de Couasnon, Travert, Monnier and all.http://www.wipo.int/pctdb/en/wo.jsp?WO=1990/04893
- October 1990: TH-CSF LER, first OFDM équipment field test, 34 Mbit/s in a 8 MHz channel, experiments in Paris area
- December 1990: TH-CSF LER, first OFDM test bed comparison with VSB in Princeton USA
- September 1992: TH-CSF LER, second génération equipment field test, 70 Mbit/s in a 8 MHz channel, twin polarisations. Wuppertal, Germany
- October 1992: TH-CSF LER, second generation field test and test bed with BBC, near London, UK
- 1993: TH-CSF show in Montreux SW, 4 TV channel and one HDTV channel in a single 8 MHz channel
- 1993: Morris: Experimental 150Mbit/s OFDM wireless LAN
- 1994: US patent 5282222 (http://v3.espacenet.com/textdoc?DB=EPODOC&IDX=US5282222) , *Method and apparatus for multiple access between transceivers in wireless communications using OFDM spread spectrum*
- 1995: ETSI Digital Audio Broadcasting standard EUreka: first OFDM based standard
- 1997: ETSI DVB-T standard
- 1998: Magic WAND project demonstrates OFDM modems for wireless LAN
- 1999: IEEE 802.11a wireless LAN standard (Wi-Fi)
- 2000: Proprietary fixed wireless access (V-OFDM, Flash-OFDM, etc.)
- 2002: IEEE 802.11g standard for wireless LAN
- 2004: IEEE 802.16-2004 standard for wireless MAN (WiMAX)
- 2004: ETSI DVB-H standard
- 2004: Candidate for IEEE 802.15.3a standard for wireless PAN (MB-OFDM)
- 2004: Candidate for IEEE 802.11n standard for next generation wireless LAN
- 2005: Candidate for 3.75G mobile cellular standards (3GPP & 3GPP2 Long Term Evolution)) named High Speed OFDM Packet Access (HSOPA)
- 2005: Candidate for 4G standards (CJK)

See also

- Cyclic prefix
- Modem
- ATSC Standards
- DVB-T
- DRM
- Telebit
- Paul Baran

References

- Chang, R. W. (1966). Synthesis of band-limited orthogonal signals for multi-channel data transmission, *Bell System Technical Journal* **46**, 1775-1796.
- Chang, R. W. & and Gibbey, R. A. (1968). A theoretical study of performance of an orthogonal multiplexing data transmission scheme (http://ieeexplore.ieee.org/xpls/abs_all.jsp?isNumber=23720&prod=JNL&arnumber=1089889&arSt=+529&ared=+540&arAuthor=+Chang%2C+R.%3B++Gibby%2C+R.
, *IEEE Transactions on Communications Technology* **16** (4), 529-540.
- Saltzberg, B. R. (1967). Performance of an efficient parallel data transmission system (http://ieeexplore.ieee.org/xpls/abs_all.jsp?isNumber=23710&prod=JNL&arnumber=1089674&arSt=+805&ared=+811&arAuthor=+Saltzberg%2C+B.&arNumber=10896
, *IEEE Transactions on Communications Technology* **15** (6), 805-811.
- de Couasnon T., Monnier R., Rault J.B. (1994) OFDM for digital TV broadcasting, Signal processing (ELSEVIER) 39 (1994) 1-32
- K. Fazel, S. Kaiser (2003), *Multi-Carrier and Spread Spectrum Systems*, John Wiley & Sons, 2003, ISBN 0-470-84899-5
- Bahai, A. R. S., Saltzberg, B. R., Ergen, M. (2004)., *Multi Carrier Digital Communications: Theory and Applications of OFDM*, Springer, 2004.

- "The how and why of COFDM" (http://www.ebu.ch/en/technical/trev/trev_278-stott.pdf) Jonathan Stott. EBU: *EBU Technical Review (http://www.ebu.ch/en/technical/trev/trev_home.html)* 278 (winter 1998).
- Leeper, David G (2007)., "WiFi - The Nimble Musician in Your Laptop", *IEEE Computer Magazine -- How Things Work*, April, 2007, pp 108-110.

Notes

1. ^ http://ec.europa.eu/archives/ISPO/infosoc/legreg/docs/dir95-47en.html
2. ^ ETSI Standard: EN 300 744 V1.5.1 (2004-11).
3. ^ http://www.citizens.coop/aboutus/newsreleases/TrulyMobileWireless.pdf

External links

- Numerous useful links and resources for OFDM (http://wcsp.eng.usf.edu/OFDM_links.html) - WCSP Group - University of South Florida (USF)
- WiMAX Forum, WiMAX, the framework standard for 4G mobile personal broadband (http://www.wimaxforum.org)
- Flarion Technologies, the inventor of FLASH-OFDM (http://www.flarion.com/products/flash_ofdm.asp)
- QUALCOMM, parent company of Flarion Technologies (http://www.qualcomm.com/about/flarion.html)
- Stott, 1997 [1] (http://www.bbc.co.uk/rd/pubs/papers/paper_15/paper_15.shtml) Technical presentation by J H Stott of the BBC's R&D division, delivered at the 20 International Television Symposium in 1997; this URL accessed 24 Jan 2006.
- Page on Orthogonal Frequency Division Multiplexing at http://www.iss.rwth-aachen.de/Projekte/Theo/OFDM/node6.html accessed on 24th Sep. 2007.
- Siemens demos 360 Mbit/s wireless (http://www.infosyncworld.com/news/n/5345.html)
- 1994 US Patent 5,282,222 for wireless data transmission (http://www.pattools.com/cgi-bin/patent_navigator.pl?patent=5282222) - The patent "tree" rooted on this patent has upwards of 20000 nodes and leaves references.

Retrieved from "http://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing"

Categories: All articles with unsourced statements | Articles with unsourced statements since October 2007 | Multiplexing | Radio modulation modes

- This page was last modified 03:04, 26 October 2007.
- All text is available under the terms of the GNU Free Documentation License. (See **Copyrights** for details.)
Wikipedia® is a registered trademark of the Wikimedia Foundation, Inc., a U.S. registered 501(c)(3) tax-deductible nonprofit charity.